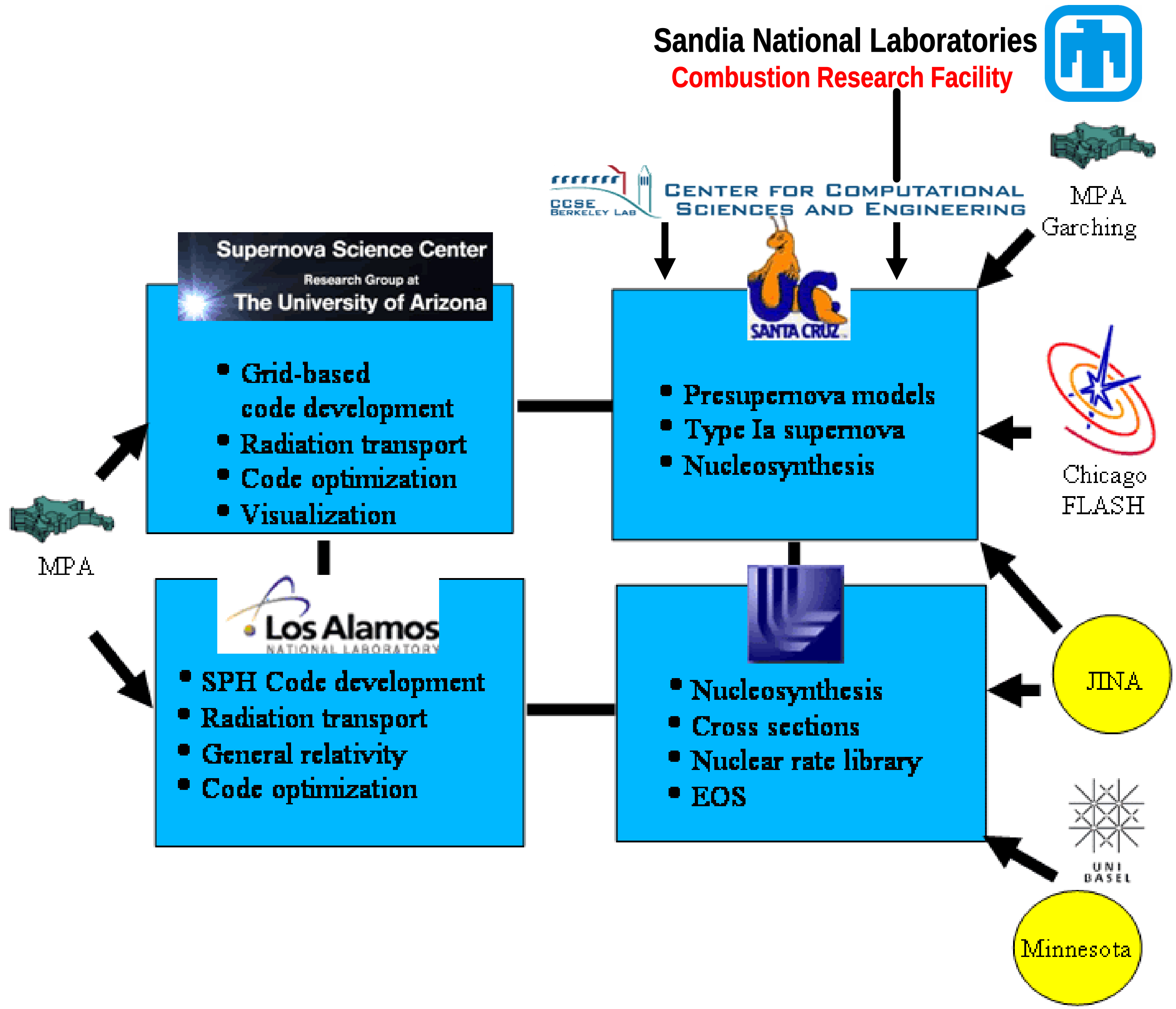
# The SuperNova Science Center (SNSC)



## Scientific Goal

*A full understanding, achieved through numerical simulation, of how supernovae of all types explode and how the elements have been created in nature. Comparison of these results with astronomical observations and with the abundance pattern seen in the sun and in galaxies.*

# The Core Team

UCSC

Woosley, Glatzmaier, Zingale, Zhang, Kuhlen, Rogers, Dobbs Dixon

LANL

Fryer, Warren, Heger, Hungerford

LLNL

Hoffman, Dietrich, Salmonson, Pruet

Arizona

Burrows, Pinto, Hariri, Sarjoughlan, Ott, Walder, Meakin, Murphy, Metchnick, Zhang, Ming, Livne, Lichenstadt

*plus a similar number of co-authors and collaborators at other institutions, about 50 people altogether.*

## Strong Collaborations (e.g., joint research papers)

Chicago FLASH Center – working on applying FLASH code to supernovae. Building on ASCI.

Sandia, Livermore, Combustion Facility – working on turbulent (nuclear) combustion

Center for Computational Science and Engineering, LBNL – working on low Mach number combustion

Joint Institute for Nuclear Astrophysics – working on the nuclear data base for nuclear astrophysics. x-ray bursts on neutron stars. RIA.

MPA – Garching – working on core collapse supernovae and Type Ia supernovae

Also collaborating with ...

Terrascale Supernova Initiative – co-organizing workshops at the INT, Aspen, and the APS. Working together on equation of state issues

Correspondence and common interests with:

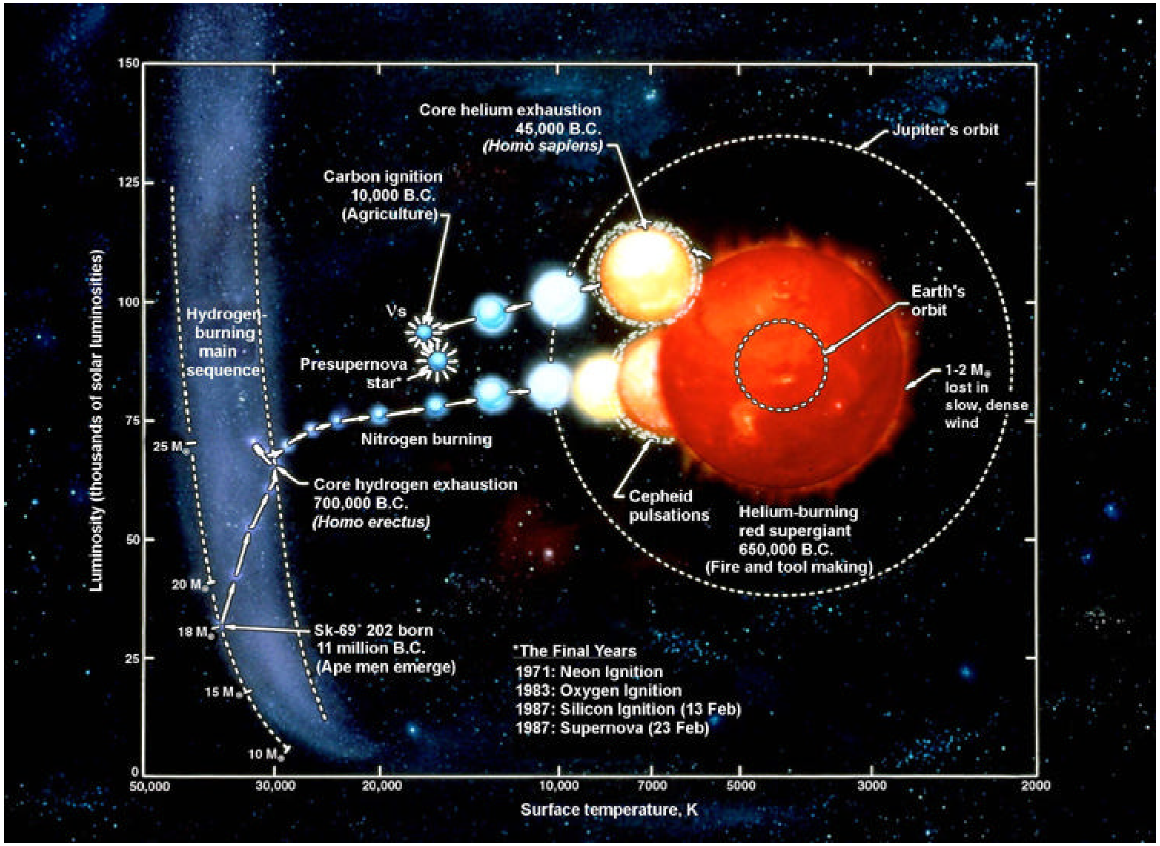
TSTT – models provided for study to Jim Glimm's group

TOPS – we presented a paper at Copper Mountain

PERC, CCA, SDM, SSSC

*A proposal has been submitted to the NSF – ITR-Large with members of several of the ISICs as co-I's.*

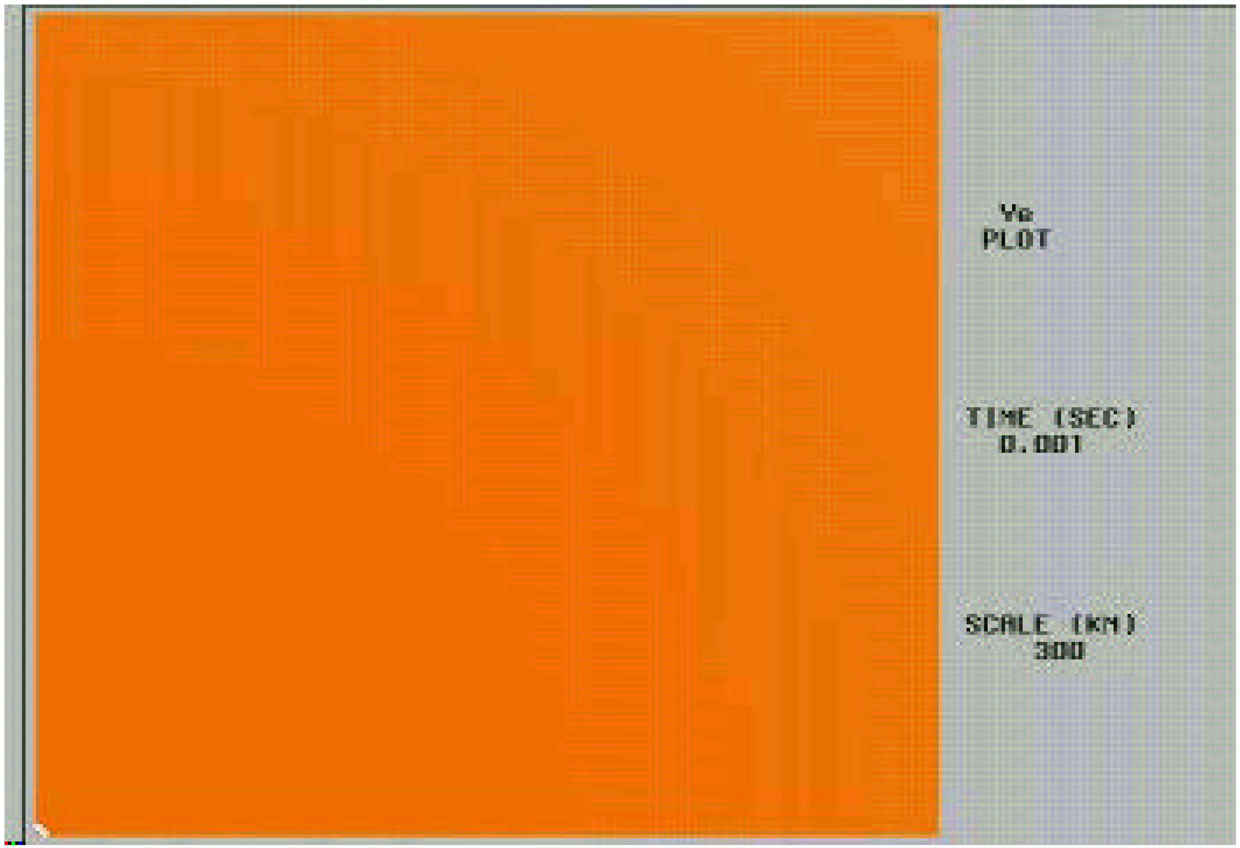
# Type II supernova: The explosive death of a massive star




## Issues:

- Multi-dimensional hydrodynamics coupled to multi-group, multi-angle, multi-dimensional neutrino transport.*
- Equation of state for supernuclear density
- Possibly magnetic fields, rotation and exotic particle physics

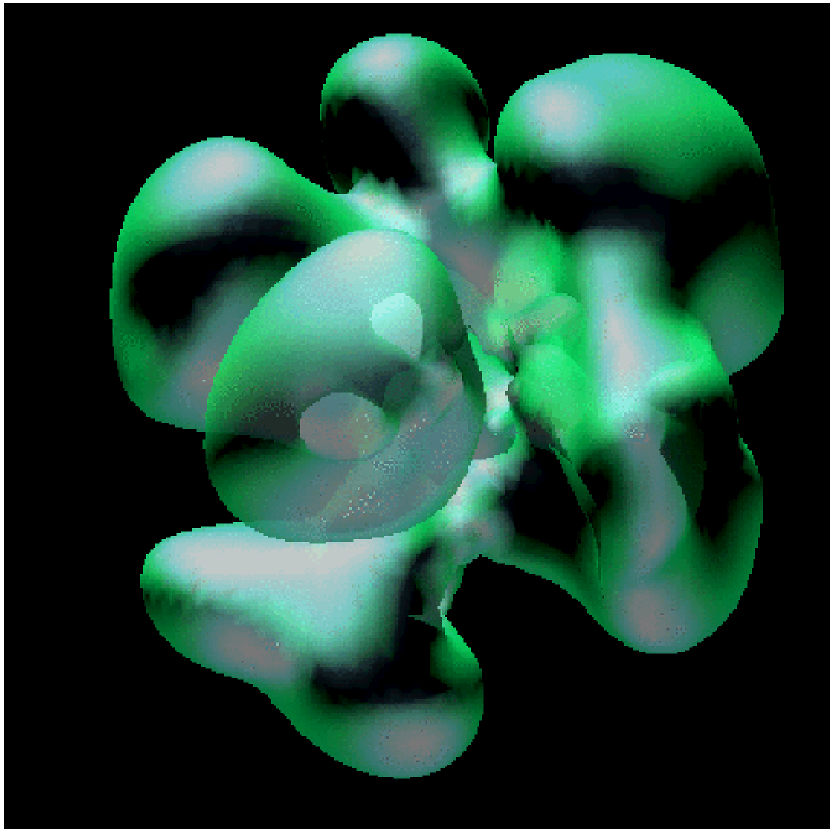
** Similar in ways to terrestrial nuclear explosions*



Ve
PLOT
TIME (SEC)
0.001
SCALE (KM)
300

*Eight leading edge studies that would not have been done (in this time frame) without SciDAC.*

| | |
|---|---|
| 5 | SN II |
| 2 | SN Ia |
| 1 | “hypernova” |



The box is 1000 km across.

***First three-dimensional calculation of a core-collapse 15 solar mass supernova.***

This figure shows the iso-velocity contours (1000 km/s) 60 ms after core bounce in a collapsing massive star. Calculated by Fryer and Warren at LANL using SPH. It explodes. Resolution is poor and the neutrinos were treated artificially (trapped or freely streaming, no gray region), but such calculations will be used to guide our further code development.

*Working with the LANL – RAGE code group on improving the radiation/neutrino transport in these calculations.*

*Fryer & Warren, ApJ, 574, L65 (2002)*

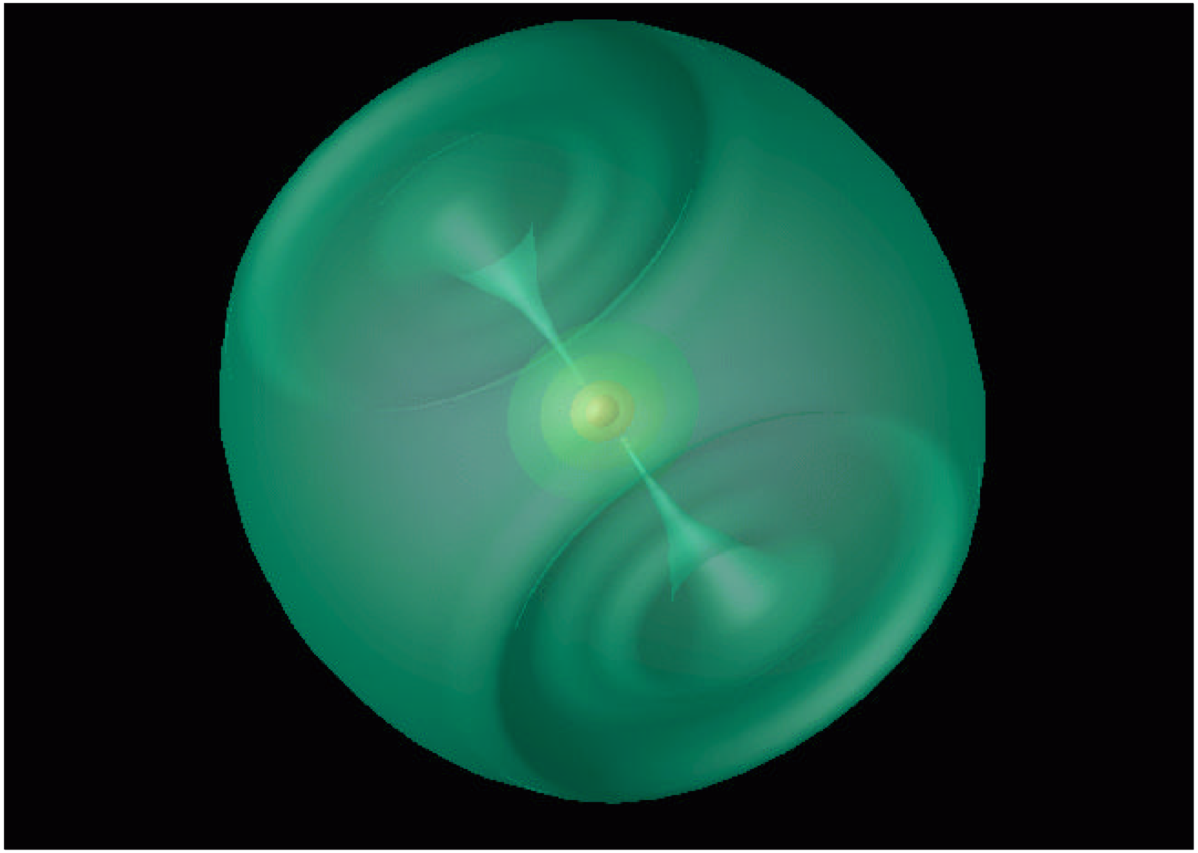
At Arizona:

- 1D calibration standard (hydro + radiation transport) complete and being published. Variable Eddington factors, Feautrier variables, tangent ray method.

- Major effort now is on VULCAN 2D
    - Arbitrary Lagrangian Eulerian mesh
    - Multi-group, multi-angle radiation transport
    - Rotation
    - Magnetic fields in progress

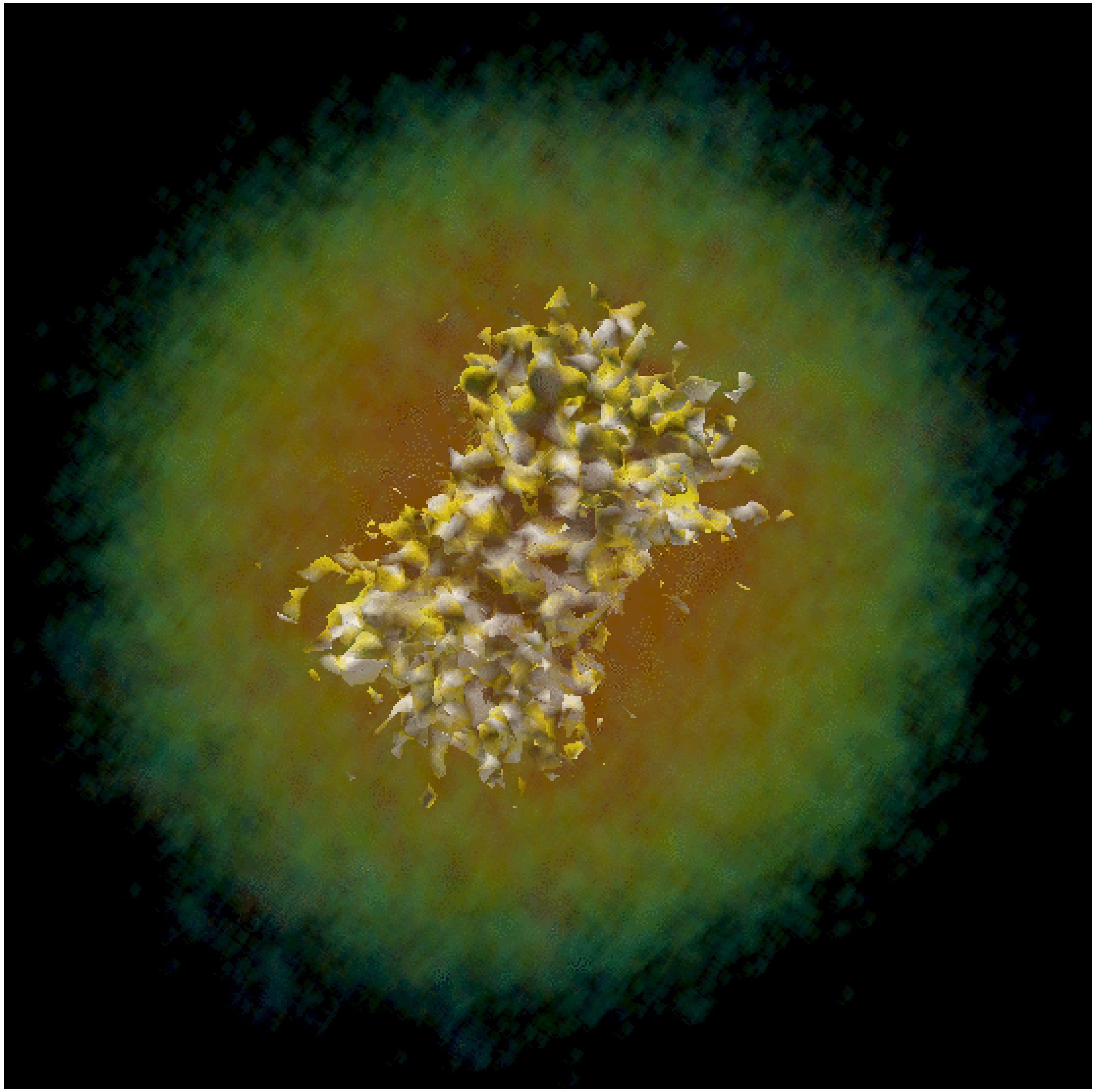
- Computer scientists working on Parallel Programming and Debugging Facility (ADViCE, PAMS) and a Runtime and Execution and Infrarstructure (CORBA, DEVS-DOC). Testing on the 1D code.

2D calculation of core collapse and bounce in an 11 solar mass supernova calculated without neutrino transport using VULCAN 2D.



1500 km at 300 ms post-bounce, no explosion

# 3D Monte Carlo Gamma-Ray Transport

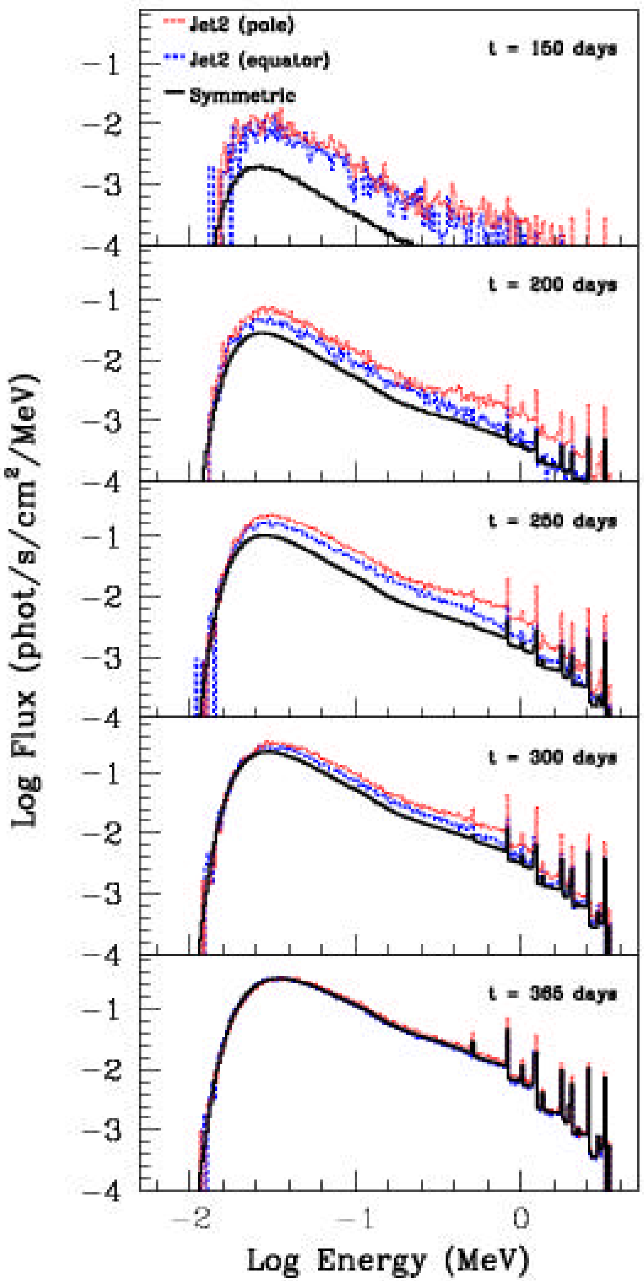


Gamma-ray energy deposition from the decay of radioactive $^{56}Ni$ in a 15 solar mass supernova also modeled with 3D hydro.

We find the Ni is mixed out farther and the gamma-ray light curve starts earlier than previously calculated in 1D models.

This is consistent with observations of SN 1987A

(Hungerford, Fryer, & Warren, ApJ, in press, astroph-0301120)

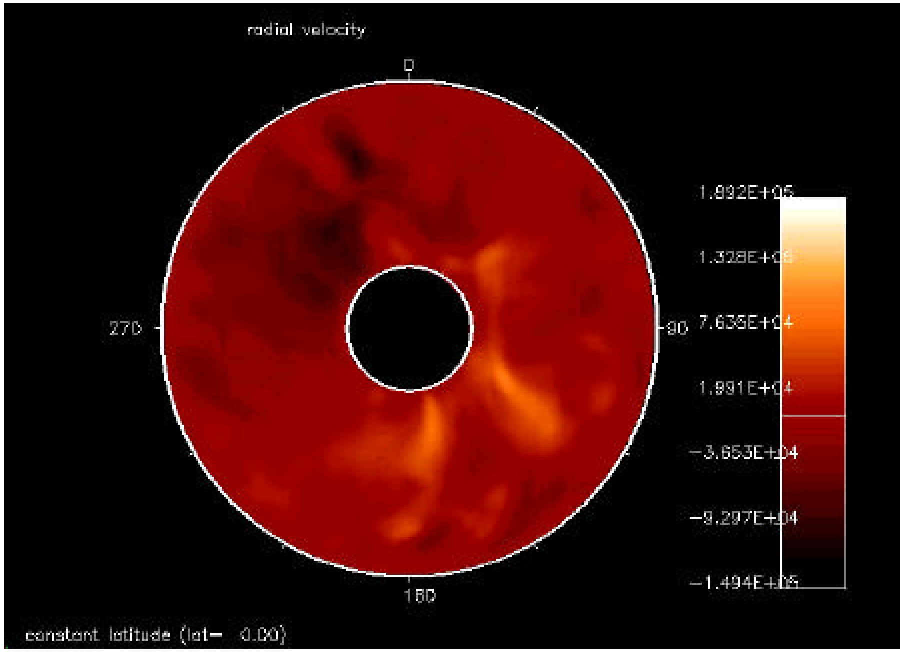



Red shows the spectrum along the polar axis

Blue is the spectrum along the equator

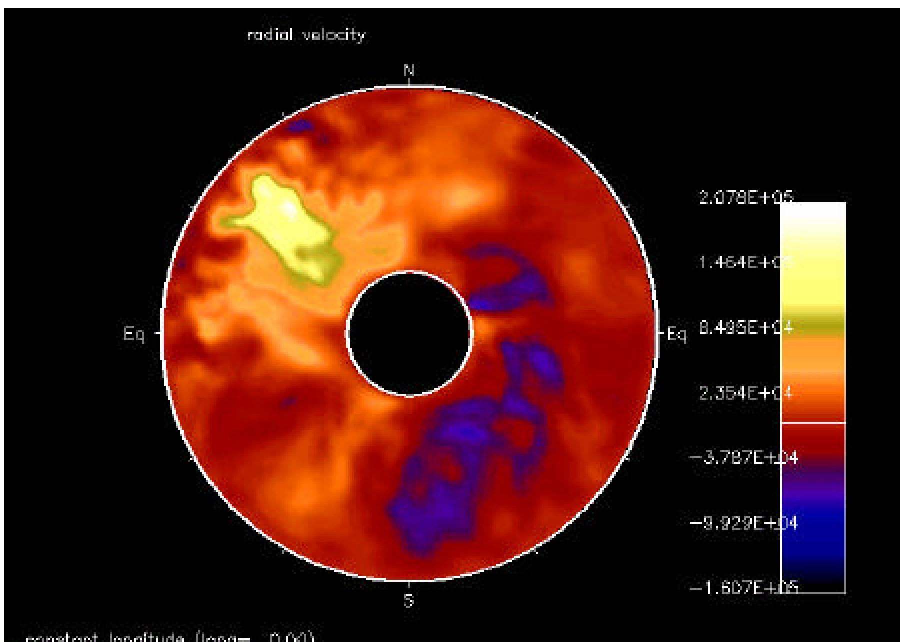
Black is the result of a spherically symmetric model

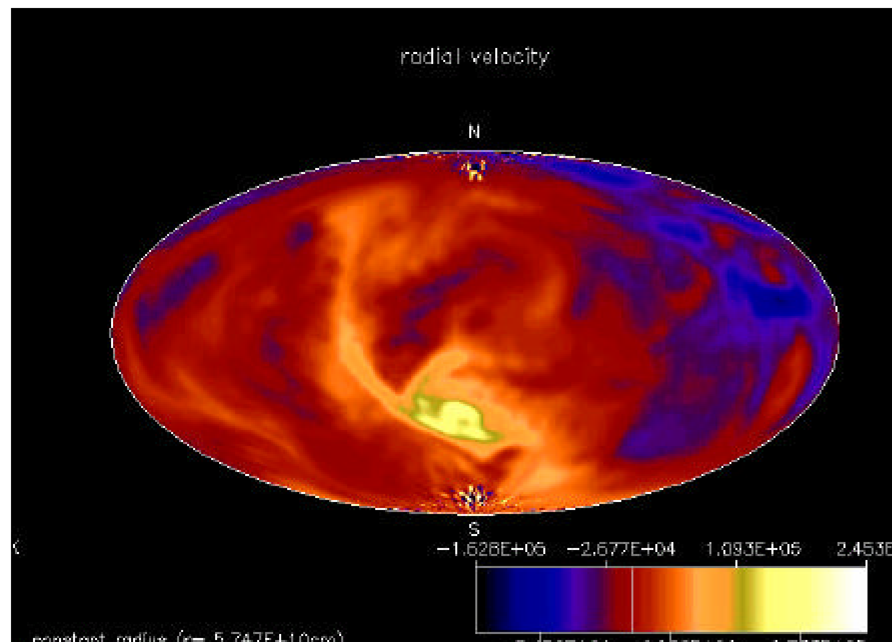
*Major flaws have been uncovered in previous published treatments of this problem!*



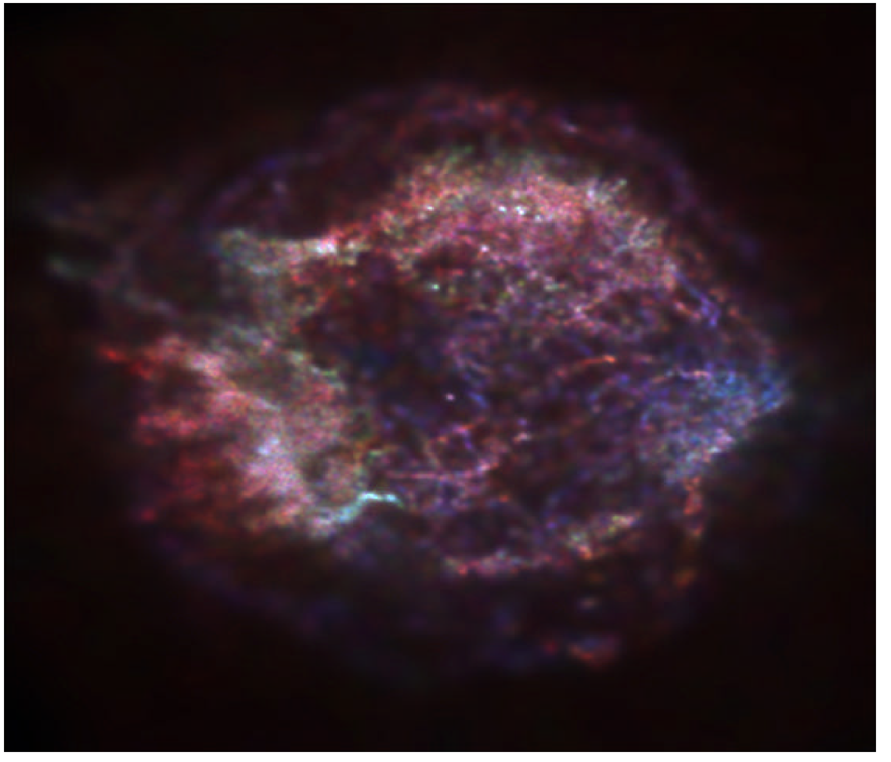

Kuhlen, Woosley, and Glatzmaier are exploring the physics of stellar convection using 3D anelastic hydrodynamics.

The model shown is a 15 solar mass star half way through hydrogen burning. For now the models are not rotating, but the code includes rotation and B-fields. (Previously used to simulate the Earth's dynamo).



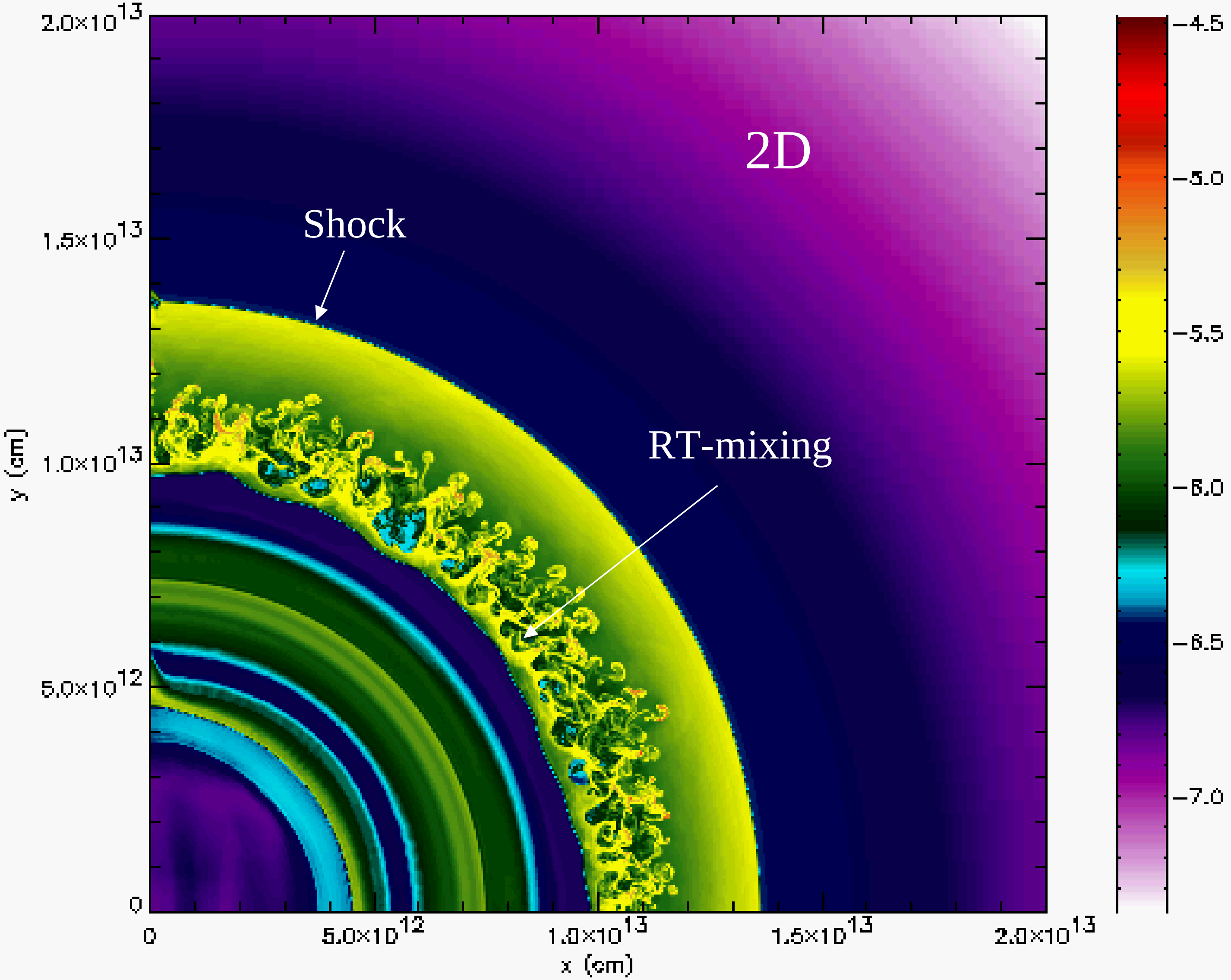
# Mixing in Supernovae



Left - Cas-A SNR as seen by the Chandra Observatory
Aug. 19, 1999

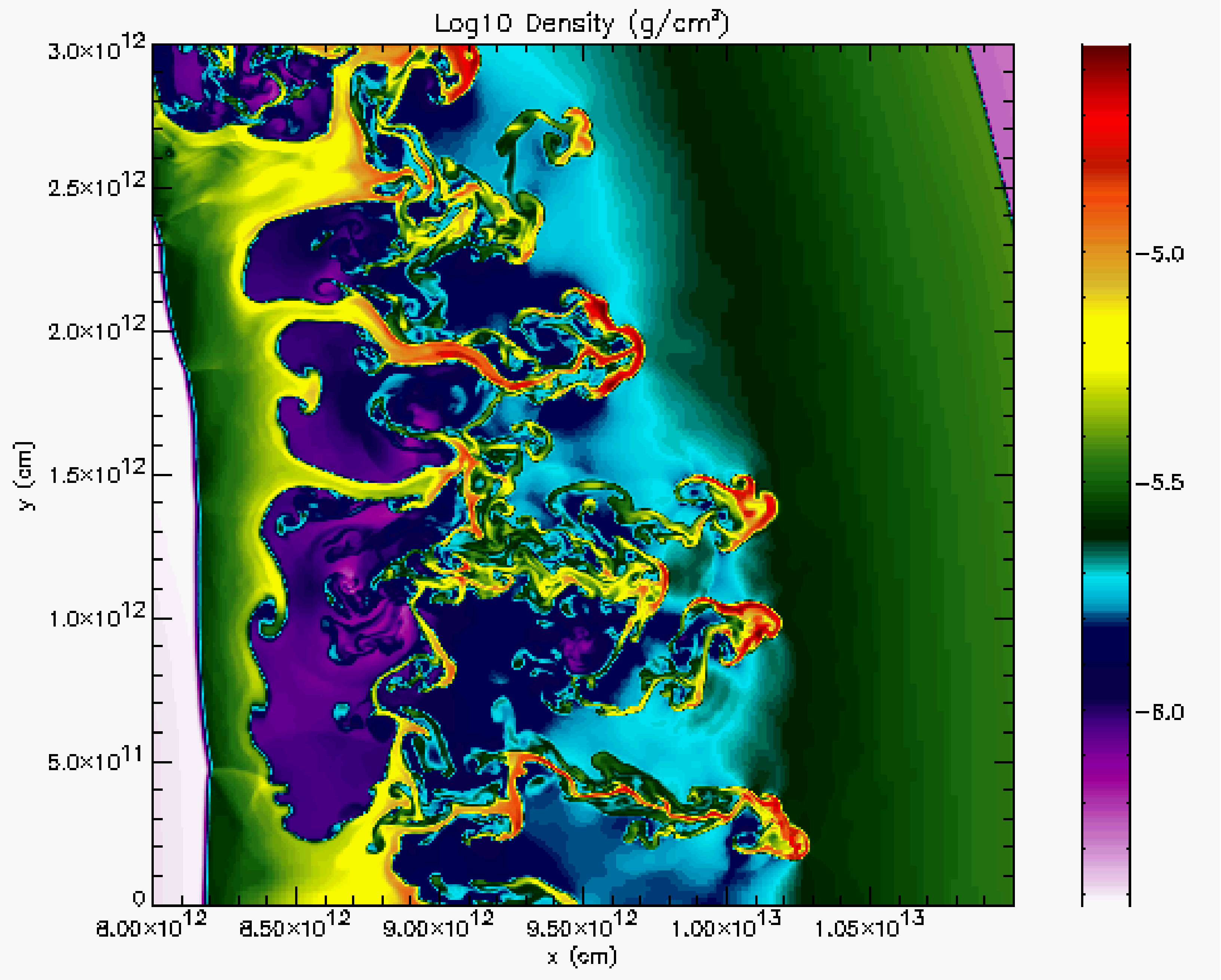
The red material on the left outer edge is enriched in iron. The greenish-white region is enriched in silicon. Why are elements made in the middle on the outside?

# 25 solar mass supernova, 1.2 x $10^{51}$ erg explosion

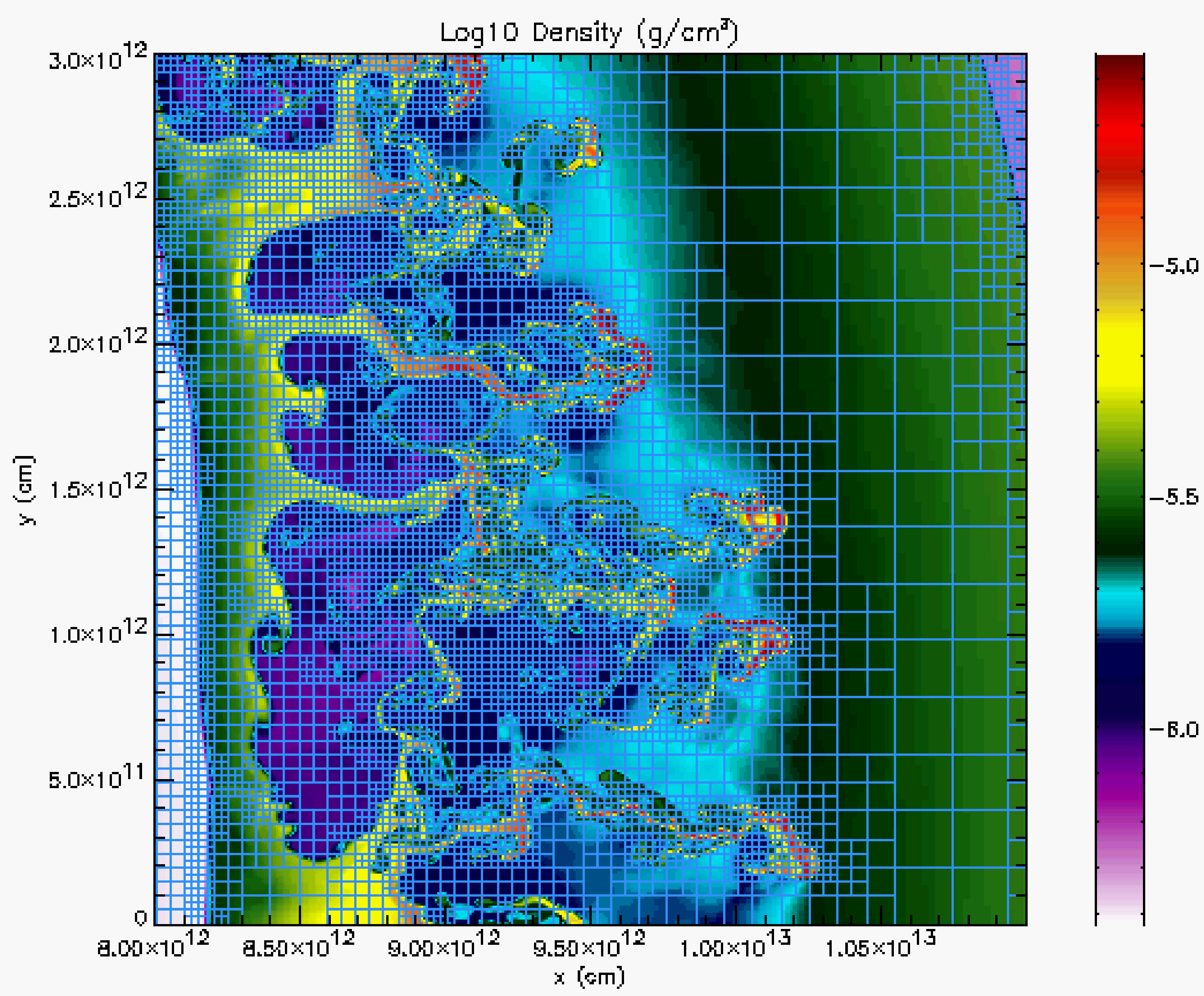



Model also provided to TSTT/Jim Glimm

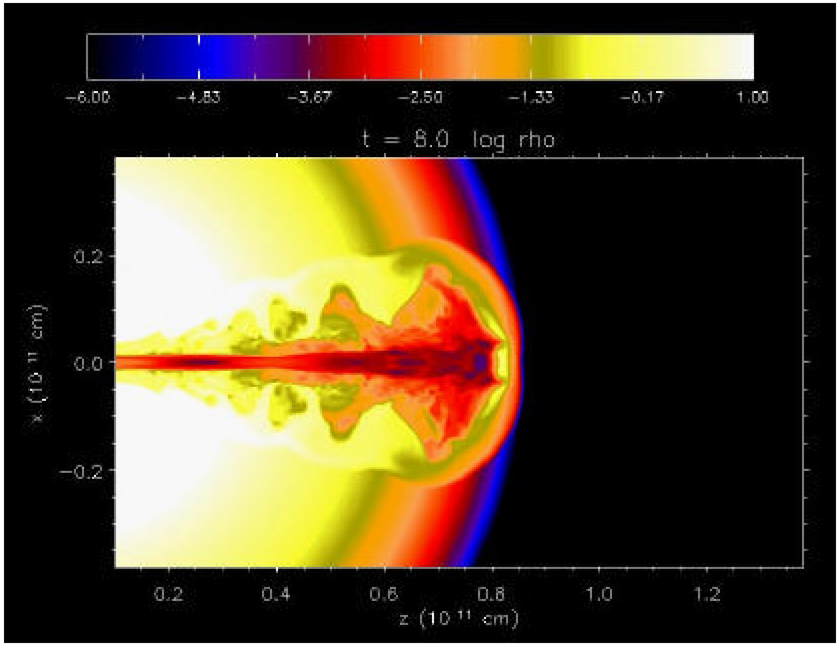
Calculation using modified FLASH code – Zingale & Woosley

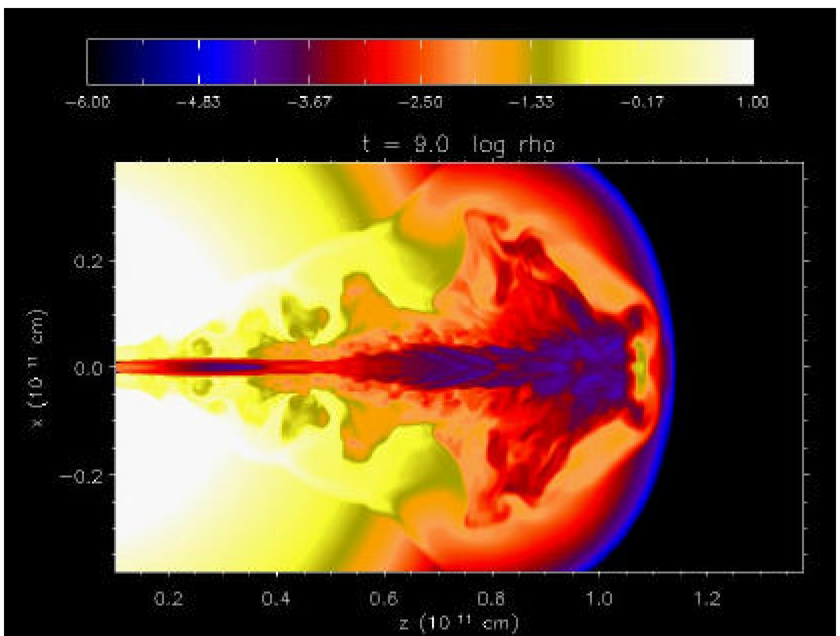


Log10 Density (g/cm³)
3.0×10¹²
2.5×10¹²
2.0×10¹²
1.5×10¹²
1.0×10¹²
5.0×10¹¹
0
y (cm)
8.00×10¹²
8.50×10¹²
9.00×10¹²
9.50×10¹²
1.00×10¹³
1.05×10¹³
x (cm)
−5.0
−5.5
−6.0



Log10 Density (g/cm³)
3.0×10¹²
2.5×10¹²
2.0×10¹²
1.5×10¹²
1.0×10¹²
5.0×10¹¹
0
y (cm)
8.00×10¹²
8.50×10¹²
9.00×10¹²
9.50×10¹²
1.00×10¹³
1.05×10¹³
x (cm)
−5.0
−5.5
−6.0



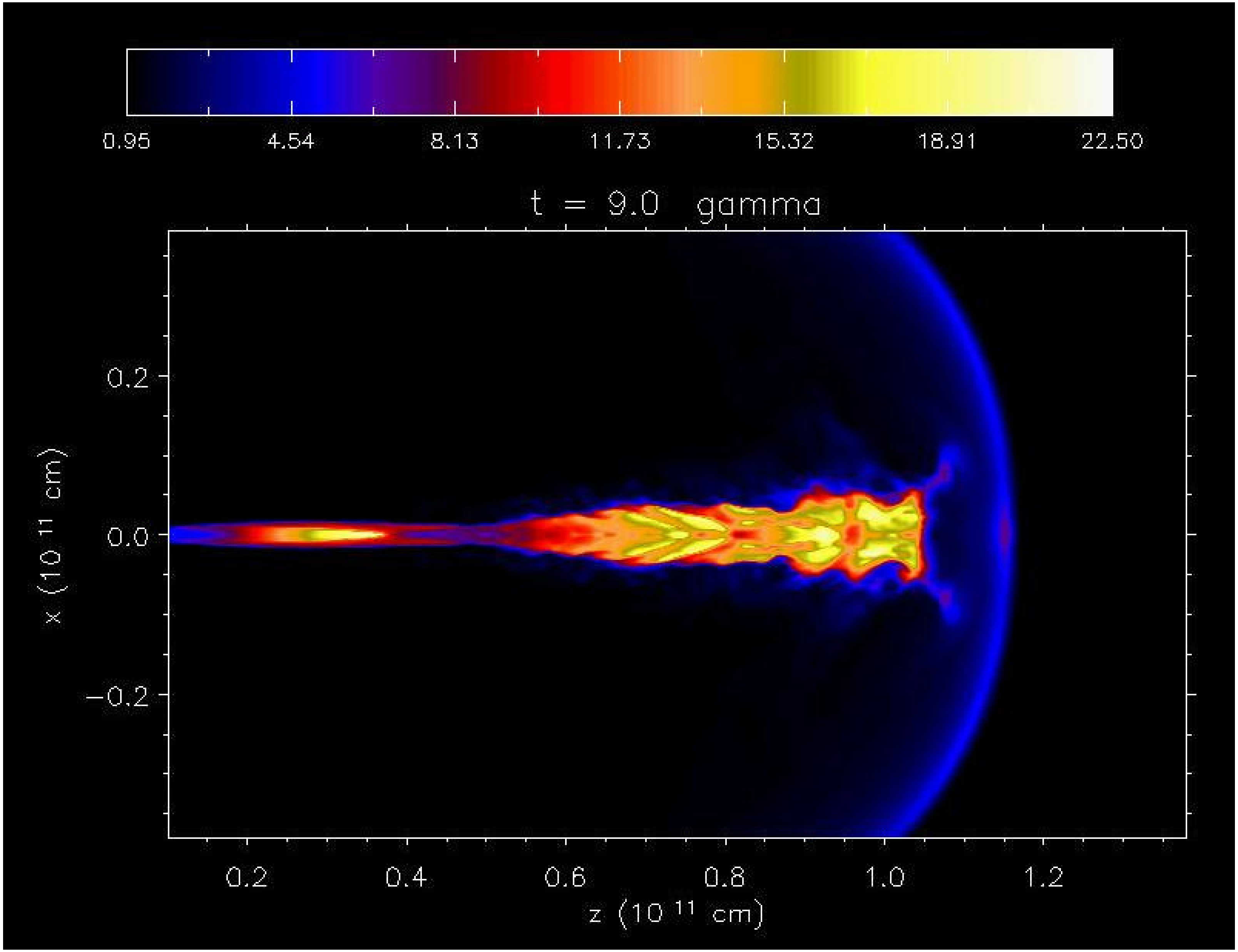




## *The collapsar model for gamma-ray bursts and "hypernovae"*

The iron core collapses to a black hole rather than a neutron star. Because the star is rotating, a disk forms around the black hole and the interaction launches a relativistic jet $\Gamma \sim 10 - 100$.

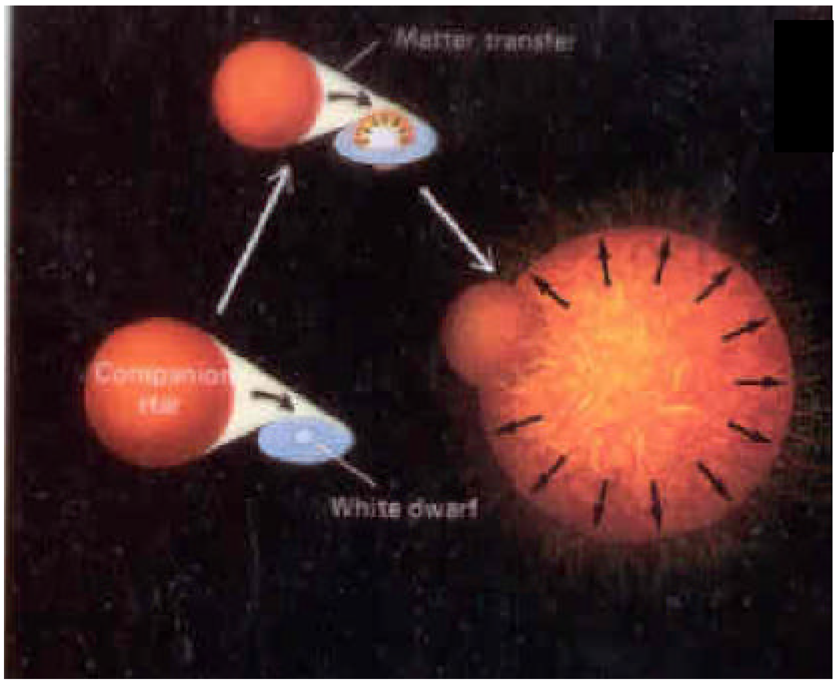
This calculation by Zhang & Woosley used approximately 10 million zones in a 3D special relativistic calculation of jet break out.

At the top – the jet nears the surface
At the bottom – the jet erupts and the cocoon of the jet explodes.



0.95
4.54
8.13
11.73
15.32
18.91
22.50
t = 9.0 gamma
0.2
0.0
−0.2
x (10 11 cm)
0.2
0.4
0.6
0.8
1.0
1.2
z (10 11 cm)

# Type Ia Supernova: The thermonuclear explosion and complete disruption of an accreting white dwarf star.

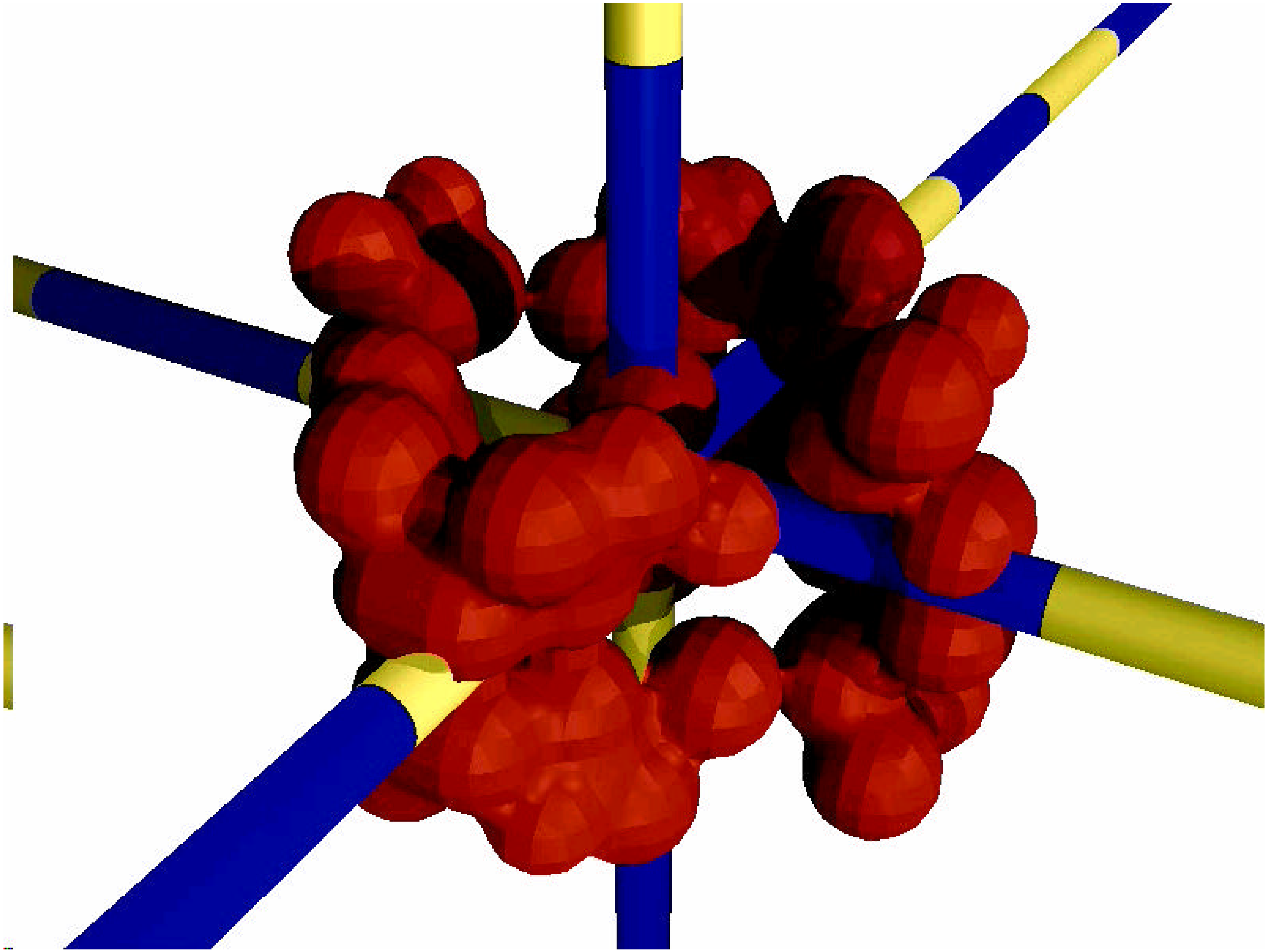



## Issues:

- Turbulent nuclear combustion – How does a highly deformed, but subsonic flame sheet propagate in the presence of turbulence? *
- How is the flame ignited – at the center or off center? Many places and times or only once?

* *similar in ways to internal combustion engines*

Reinecke et al. (2002)



Algorithmic and Software Framework - ISIC

CCSE BERKELEY LAB CENTER FOR COMPUTATIONAL SCIENCES AND ENGINEERING

*John Bell* *Charles Rendleman* *Marc Day*

*in collaboration with Mike Zingale, S. Woosley*

Chemical combustion code – adaptive mesh – low Mach number

2D and 3D - Eulerian. Parallel – runs at NERSC

Can use general equation of state and energy generation

# Nuclear fusion flame in carbon-oxygen mixture

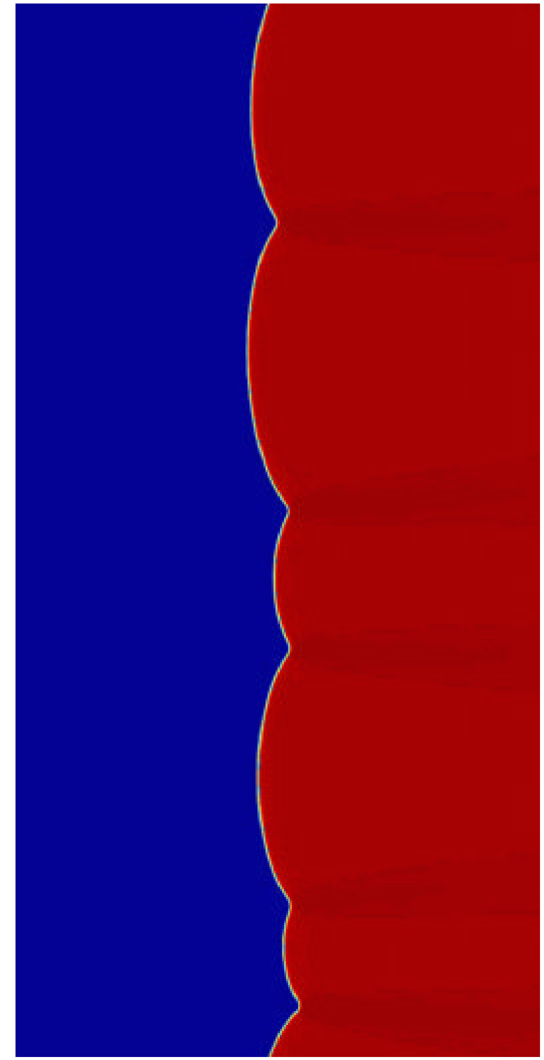
$r = 5\, x 10^{7}$ gm cm$^{-3}$

$T = 10^{7}$ K

$u_{lam} = 7$ km s$^{-1}$ (about 0.1% sound speed)

box is 2 cm x 6 cm
3 levels of refinement

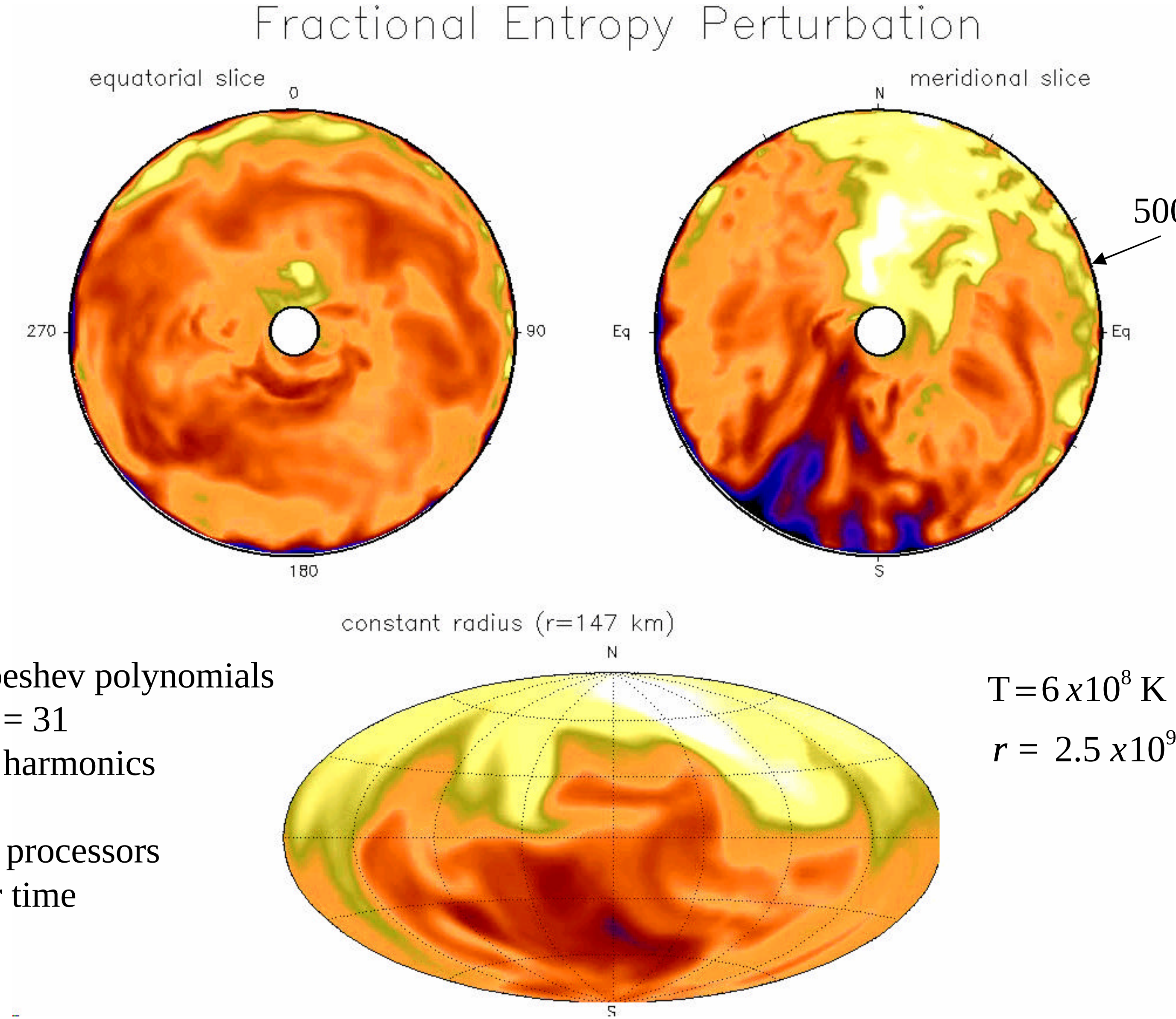
enormously faster and more accurate than explicit hydrodynamics (by a factor ~ sound speed/$u_{lam}$ )



Landau-Darrieus instability)

# White dwarf ignition – the ramp up to Type Ia Supernova

3D




500 km

501 Chebeshev polynomials
l = 63, m = 31
spherical harmonics

22 hrs 96 processors
100 s star time

Ra = $10^{8}$.

$T = 6\,x10^{8}$ K

$r = 2.5\,x10^{9}$ gm cm$^{-3}$

# FUTURE PRIORITIES

- A full 2D model for core collapse with credible neutrino transport coupled to multi-D hydro (by year’s end)
- Further development of the FLASH code and/or the LANL RAGE code as a platform for 3D supernova studies
- Complete nucleosynthesis survey across all masses and metallicities (1D)
- Studies of the LD instability coupled to turbulence, and other flame physics studies with the LBNL and Sandia groups
- Further studies of the collapsar model for hypernovae and gamma-ray bursts